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A Time-Efficient Methodology for Visualizing Time-Varying Magnetic Flux Patterns of Mid-Range Wireless Power Transfer Systems

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Abstract— Visualizing the magnetic flux paths for wireless power transfer systems enables researchers and engineers understand the operations and design the geometrical dimensions of the practical systems. However, time-domain transient simulations of 3-D electromagnetic fields of complex wireless power transfer systems with multiple coil-resonators are extremely time-consuming. This paper describes a fast hybrid method that combines the time-domain coupled circuit modeling and the magnetostatic analysis to form a fast time-domain analytical tool for studying complex wireless power transfer systems. The proposed methodology has been successfully applied to several wireless domino-resonator systems. For the first time, the time-varying magnetic flux variations of wireless power domino-resonator systems can be visualized in computer simulations.

I. INTRODUCTION

Mid-range wireless power transfer systems with multiple coil-resonators have recently been investigated for their capability of transferring energy with relative high power and their flexibility of physical dimensions and positions of the coils [1]-[6]. So far, their analyses rely on coupled circuit models, which however do not provide any information about the time-varying magnetic flux paths and visual information of the spatial magnetic flux interactions of various coil-resonators and the loads.

Commercial software such as Ansoft Maxwell can perform transient analysis for the system with given dimensions of the windings of the coils as well as the serial capacitances and resistances of the resonator circuits [7]. If high precision is required, however, the transient analysis based on the Maxwell 3D Electromagnetic Solver is extremely time-consuming and substantial computation resources are required. Taking a wireless power system with 7 resonator-coils as an example and assuming that a desktop personal computer is used, the simulation time from the start-up to the steady-state operation will take over 10 hours, without guarantee of convergence, to reach reasonable solutions. When more resonator coils are used in the wireless power system, the longer it will take to reach final steady state solution of the whole system.

In this paper a time-efficient method is proposed as a simulation tool to study complex wireless power systems. The

proposed method combines the uses of coupled circuit model and the magnetostatic analysis of the finite-element software to obtain fast solutions and magnetic field plots at various points of time within an excitation cycle. The coupled circuit model allows the steady-state solutions to be obtained for each timeframe. The solutions are used by the magnetostatic analysis software to obtain the 3D magnetic field plots. Then the successive magnetic field plots can be displayed in a time sequence to provide the visual information of the time-varying magnetic field in the wireless power transfer systems. This approach is demonstrated in computer studies of straight, circular and Y-shaped wireless power domino-resonator systems [4]-[6].

II. MODEL AND METHODOLOGY

Fig. 1 shows the lumped circuit model of a domino-resonator system with n resonators. Its circuit equation is expressed with (1). Here, as shown in Fig. 2, the self-inductance of the u^{th} coil is denoted by L_u and the mutual inductance between the u^{th} and v^{th} coils is denoted by M_{uv} ($u > v$). The AC resistance of the resonator is R_u . The capacitance in the u^{th} resonator is denoted by C_u and the voltage source and the current are denoted by V_{Su} and I_u , respectively.

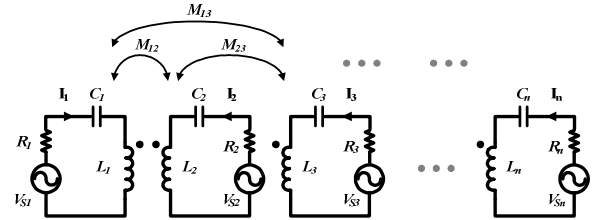


Fig. 1. Coupled circuit model of a wireless power system with n coil-resonators

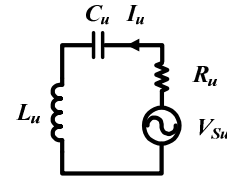


Fig. 2. Circuit model of Resonator- u in a domino-resonator system

The currents of all the resonators (\mathbf{I}_1 to \mathbf{I}_n) can be calculated provided that the system parameters in (1) are known, or can be obtained by calculation or measurement. Then the currents can be used in a static magnetic analysis to plot the magnetic flux pattern of the entire system for a particular point in time. Then successive magnetic flux plots

can be obtained over a period of time. This approach will take much less time in comparison with transient analysis and can be implemented on normal personal computers. The flow chart of the proposed method is given in Fig. 3.

$$\begin{bmatrix} R_1 + jX_1 & j\omega M_{12} & j\omega M_{13} & \cdots & \cdots & j\omega M_{1n} \\ j\omega M_{12} & R_2 + jX_2 & j\omega M_{23} & \cdots & \cdots & j\omega M_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ j\omega M_{1(n-1)} & \cdots & \cdots & \cdots & R_{n-1} + jX_{n-1} & j\omega M_{(n-1)n} \\ j\omega M_{1n} & \cdots & \cdots & \cdots & j\omega M_{(n-1)n} & R_n + jX_n \end{bmatrix} \cdot \begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \vdots \\ \mathbf{I}_{n-1} \\ \mathbf{I}_n \end{bmatrix} = \begin{bmatrix} \mathbf{V}_{s1} \\ \mathbf{V}_{s2} \\ \vdots \\ \mathbf{V}_{s(n-1)} \\ \mathbf{V}_{sn} \end{bmatrix} \quad (1)$$

where $X_u = \omega L_u - 1/(\omega C_u)$.

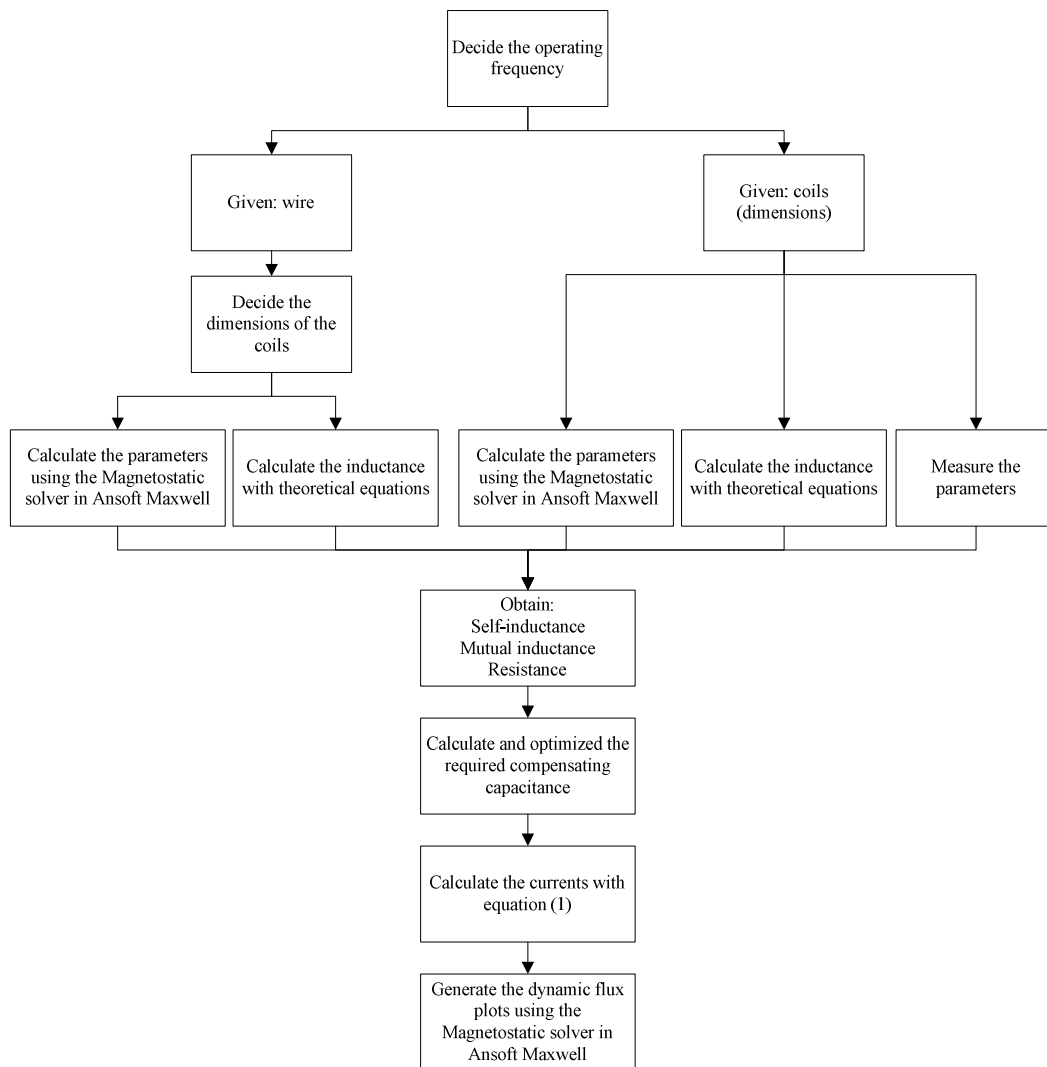


Fig. 3 Flow chart of the proposed methodology for the domino-resonator systems design

The procedures of the proposed methodology are explained as follows:

Step 1: Determination of the Operating Frequency of the System (f)

The operating frequency of the system should firstly be decided according to the practical requirements such as the resonance frequency of the resonators including their cross-coupling effects [3], the power level of the wireless power transfer system, the power losses and energy efficiencies of switching devices and the overall system, and other EMC issues.

Step 2: Determination of the Physical Dimensions and Relative Positions of the Windings (L, M, R)

Once the diameter of the wire's cross section, the shape and the size of the winding and the number of turns are determined, the self-inductance of the windings and the mutual inductance between every two windings can be calculated with analytical equations or with FEA [7]. Here are the calculation equations for the mutual inductances between two circular coils.

1. Mutual inductance for coaxial circular coils

Maxwell [8] has derived an equation to calculate the mutual inductance between two coaxial circular filamentary current loops:

$$M = \mu_0 \frac{\sqrt{r_1 r_2}}{g} [(2 - g^2)K(g) - 2E(g)] \quad (2)$$

where $K(g)$ and $E(g)$ are complete elliptic integrals of the first and second kind, respectively, $\mu_0 = 4\pi \times 10^{-7}$ H/m and

$$g = \sqrt{\frac{4r_1 r_2}{d^2 + (r_1 + r_2)^2}} \quad (3)$$

where r_1 , r_2 , and d are the radius of loop-1, loop-2 and the distance between them, respectively.

For two coaxial circular thin-wall windings, if the dimension of the wire is relatively small comparing to the dimension of the coils so that each turn of the windings can be considered as a filamentary current loop, then the mutual inductance between the two windings can be calculated by

$$M = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} M_{ij} \quad (4)$$

where n_1 and n_2 are the numbers of turns of the two windings; M_{ij} is the mutual inductance between the i turn of the first winding and the j turn of the second winding which can be worked out with (2).

2. Mutual inductance for non-coaxial resonators

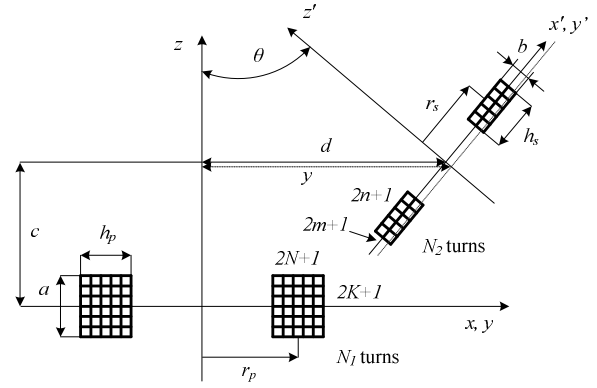


Fig. 4. Two non-coaxial circular coils.

Consider two circular coils with angular misalignment as shown in Fig.4. The mutual inductance equation proposed in [9] for non-coaxial coils (see Fig. 4) is:

$$M = \frac{N_1 N_2 \sum_{g=-K}^K \sum_{h=-N}^N \sum_{l=-n}^n \sum_{p=-m}^m M(g, h, l, p)}{(2K+1)(2N+1)(2n+1)(2m+1)} \quad (5)$$

where

$$M(g, h, l, p) = \frac{\mu_0}{\pi} \sqrt{r_p(h)r_s(l)} \int_0^\pi \frac{(\cos \theta - \frac{y(p)}{r_s(l)} \cos \phi) \Psi(k)}{V^{3/2}} d\phi$$

$$V = \sqrt{1 - \cos^2 \phi \sin^2 \theta - 2 \frac{y(p)}{r_s} \cos \phi \cos \theta + \frac{y^2(p)}{r_s^2}}$$

$$\Psi(k) = \left(\frac{2}{k} - k\right) K(k) - \frac{2}{k} E(k) = Q_{1/2}(x), x = \frac{2-k^2}{k^2}$$

$$y(p) = d + \frac{b \sin \theta}{2m+1}, p, p = -m, \dots, 0, \dots, m$$

$$r_p(h) = r_p + \frac{h_p}{2N+1} h, h = -N, \dots, 0, \dots, N$$

$$r_s(l) = r_s + \frac{h_s}{2n+1} l, l = -n, \dots, 0, \dots, n$$

$$z(g, p) = c + \frac{a}{2K+1} g - \frac{b \cos \theta}{2m+1} p,$$

$$g = -K, \dots, 0, \dots, K, p = -m, \dots, 0, \dots, m$$

$$k^2 = \frac{4\alpha V}{(1 + \alpha V)^2 + \xi^2},$$

$$\xi = \beta - \alpha \cos \phi \sin \theta,$$

$$\alpha = \frac{r_s}{r_p(h)},$$

$$\beta = \frac{z(g, p)}{r_p(h)}$$

r_p radius of the larger coil;

h_p thickness of the larger coil;

a axial length of the larger coil;

r_s radius of the smaller coil;

h_s thickness of the smaller coil;

b axial length of the smaller coil;

- c distance between coils' centers;
- d distance between coil planes;
- θ angle between axes;
- $K(k)$ complete elliptic integral of the first kind;
- $E(k)$ complete elliptic integral of the second kind;
- $Q_{1/2}(k)$ Legendre function of the second kind and half-integral degree

Several practical examples are provided in [4]-[6] and they show that the calculated values of inductance are in good agreement with the measured values. Also, the AC resistance of the windings can be obtained by using the method proposed in [10] or by measurement if the windings are available.

Step 3: Determination of the Values of the Compensating Capacitors

The capacitances are chosen to match the best operating situation, based on either the maximum power transfer or maximum power efficiency principle [11]. Numerical optimization tool could be used to get the optimum values for the capacitors.

Step 4: Calculation of the Coil Currents

The operating frequency, inductances, resistances and capacitances can be put into (1), which can then be solved to get the values of the currents.

Step 5: Magnetic Flux Calculation and Plots

At each time point, the magnitude of the currents can be worked out and used in a static FEA analysis to produce the magnetic flux pattern of the system for this point in time. By repeating this step at different points in time within each excitation cycle, the flux plots at the successive points of a cycle can be obtained. Thus the magnetic flux variation can be displayed in the time sequence to form a time-domain animation of the magnetic behavior of the wireless power transfer systems.

III. SIMULATION RESULTS

A. Implementation Issues

The proposed methodology is now applied to the straight, circular and Y-shaped wireless power domino-resonator systems. Details of these systems can be obtained in [4]-[6]. The magnetic flux pattern can be presented in the vector form or contour form. For clear visualization in a computer screen, the outer surface of the contours can be displayed in the time sequence of the magnetic field plots. Since the contours only indicates the density of the flux lines and not the direction of the flux lines, the magnetic flux plots within the first half of the ac excitation cycle are needed. The time-varying magnetic flux variation in the second half of the cycle can be re-constructed based on the magnetic flux plots of the first half-cycle.

For this computer simulation study, the windings of the coil-resonators are identical. Each circular winding consists of 11 turns with a coil diameter of 30cm, a winding width of 2cm and a winding thickness of 1.5mm. Each coil is connected in

series with a capacitor of 1nF. The 1st coil in each system is connected with the source and is used as the transmitter coil.

When compared with the transient analysis method of the finite-element EM Field solver, the proposed method is more time efficient. For a transient analysis of a wireless power system with 7 coils, it takes more than 10 hours for the transient solver in Ansoft Maxwell to obtain a solution on a normal desktop personal computer if the time step is set at 1/100 of the operating period with 1000 fragments for each coil. If more accurate results are needed, the time steps should be smaller and the number of fragments should be larger, meaning that much longer time will be needed. The proposed method, however, takes only 5 to 10 minutes for plotting the magnetic flux for one particular time point in the period on a desktop computer.

B. Simulation and Observation

Fig.5 shows the magnetic flux contours of 5 wireless power domino-resonator systems at different angles of an excitation cycle. Each magnetic flux pattern is generated by the proposed methodology. These contours can be linked up and displayed in their respective time sequence so that their time-varying behaviors can be visualized.

1) Straight domino system

For the straight domino system, visualization of the time-varying expansion and contraction of the magnetic flux contours shows that wireless power flows from the transmitter coil to the receiver coil like a heart pumping blood through a blood vessel.

2) Two circular domino systems

Two circular domino systems, one with 7 resonators and the other with 8 resonators are also examined with the proposed method. In [6], it has been pointed out the circular domino systems with odd number of resonators may face flux cancellation issues. This phenomenon can be observed in the circular domino system with 7 coils when the magnetic flux contours are displayed in the time sequence. But for the circular domino system with 8 coils, the flux pattern is symmetrical as time varies.

3) Two Y-shaped domino systems

Two Y-shaped domino systems with two loads are examined. One system has unequal loads of 10 Ω and 20 Ω , while the other system has two identical loads of 10 Ω . For the system with unequal loads, the flux patterns show that there is a phase shift between the magnetic contours in the two receiving branches. But for the system with identical loads, the flux contours in the two receiving branches are symmetrical.

IV. CONCLUSION

A fast methodology of generating time-varying visual images of the magnetic flux patterns for wireless power transfer systems is presented. It combines the fast calculation of the coupled circuit model and the time-efficient

magnetostatic analysis together as a tool for studying the behavior of wireless power transfer systems. This approach overcomes the time-consuming problem of the time-domain transient electromagnetic field 3D solver and enables researchers to visualize the time-varying flux patterns in wireless power transfer systems. For the first time, the visual images of the magnetic flux contours displayed in the time sequence have enabled us to explain the behavior of straight, circular and Y-shaped domino-resonator systems.

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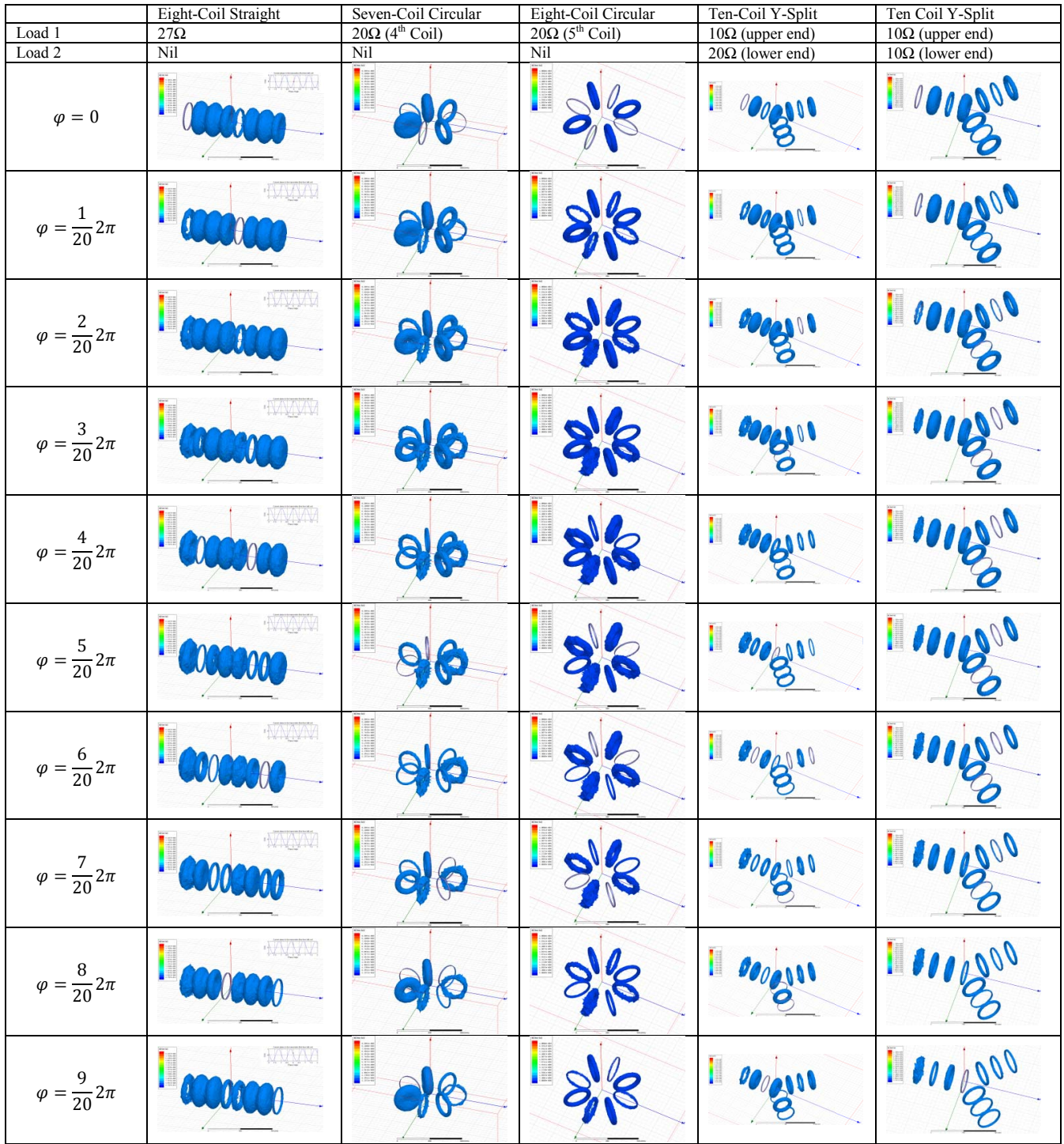


Fig.5 Magnetic flux contours of 5 wireless power domino-resonator systems (displayed in their respective sequence for half of the excitation cycle)